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**Citation for published version:**

Stratford, T 2010, Unbonded FRP to Improve the In-Plane Performance of Masonry Panels. in M Forde (ed.), *Structural Faults and Repair 2010*. Edinburgh, Structural Faults and Repair 2010, Edingburgh, United Kingdom, 15/06/10. <<http://www.structuralfaultsandrepair.com/>>

**Link:**

[Link to publication record in Edinburgh Research Explorer](#)

**Document Version:**

Publisher's PDF, also known as Version of record

**Published In:**

Structural Faults and Repair 2010

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# UNBONDED FIBRE-REINFORCED POLYMER TO IMPROVE THE IN-PLANE PERFORMANCE OF MASONRY PANELS

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**KEYWORDS:** Masonry, FRP, strengthening, unbonded, adhesive, ductility.

## ABSTRACT

Bonded fibre-reinforced polymer (FRP) strengthening has become a popular method for retrofitting masonry structures, but it is accompanied by onerous surface preparation and large quantities of polymeric adhesive. Both have health and safety implications, can be undesirable on a heritage structure, and the resulting adhesive joint is brittle. This paper reports on preliminary demonstration tests that investigate the use of unbonded FRP 'bandages' to increase the in-plane shear performance of masonry panels. It demonstrates that the elastic deformation of the FRP can be matched to the crack opening to increase the deformation capacity, ductility, and the load capacity of the masonry.

## INTRODUCTION

Fibre reinforced polymer (FRP) is an increasingly popular material for 'strengthening' masonry structures, whether the requirement is for increased load capacity, improved structural integrity, improved dynamic performance, to make good construction errors, to account for foundation movement, or to enable a change in the structural form (De Lorenzis *et al.*, 2008; Triantafillou, 1998). FRP retrofitting is often chosen due to its ease of installation, the lightweight materials used, and their low corrosion rates.

FRP strengthening is usually bonded to an existing structure as either preformed strips of FRP or by 'wallpapering' with dry fabric. Bonded FRP requires extensive surface preparation of the masonry prior to installation, and uses large quantities of organic bonding and saturating adhesives. This results in:

- Significant health and safety implications during the surface preparation and bonding operations.
- The use of large quantities of toxic organic adhesives.
- Irreversible change, which may not be acceptable for heritage buildings, in particular due to surface preparation.
- FRPs are impermeable to moisture transport, important in masonry that naturally 'breathes'.
- Bonded FRP strengthening has poor fire performance, due to the use of ambient-cure epoxy adhesives that give off toxic fumes (Stratford *et al.*, 2009).
- The scope of research to date is relatively limited, and prior application should not be confused with proof that the system works.
- The long-term reliability of the bonded systems is largely unproven.

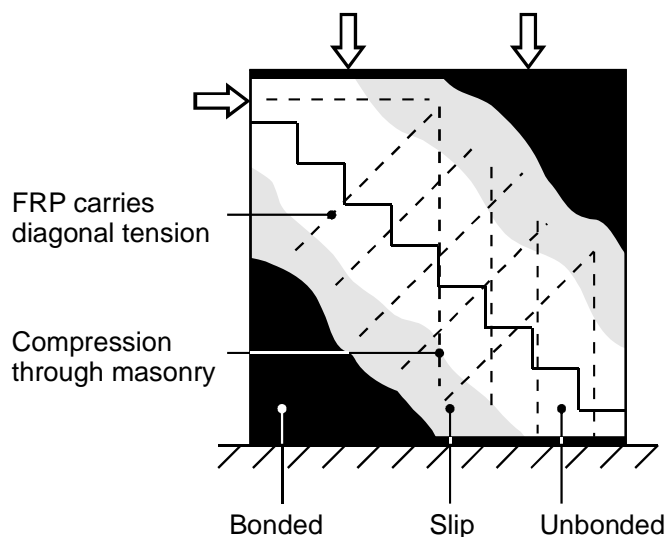
Furthermore, both the FRP strengthening and the adhesive joint are brittle, and thus susceptible to imperfection sensitivity (including unknown defects within the masonry), a lack of energy dissipation during cyclic loading, and an inability to redistribute load paths if unforeseen loads are applied to a structure.

This paper describes preliminary small-scale tests on masonry specimens strengthened for in-plane shear using unbonded FRP 'bandages' (described below). The aim of the work is to investigate a method of

FRP strengthening that does not require widespread surface preparation, does not require large quantities of adhesive (resulting in potentially improved fire performance), is less reliant on workmanship, is less prone to defects, improves the reversibility of installation, and exploits the ductility present within the masonry.

#### FRP FOR IN-PLANE SHEAR STRENGTHENING OF MASONRY

Bonded FRP strengthening can be used to increase the load-capacity of masonry panels carrying in-plane shear (e.g.: Schwegler, 1995; Marshall *et al.*, 1999; Stratford *et al.*, 2004). The FRP only carries significant load once the masonry has become cracked due to the in-plane shear (Fig. 1a).



(a) The load-carrying mechanism at failure of bonded FRP strengthening.



(b) Debonding of FRP strengthening from masonry, showing failure beneath the surface of the masonry.

Fig. 1 Bonded FRP in-plane shear strengthening (Stratford *et al.* 2004).

The load capacity of the masonry is increased (i) due to the diagonal tensile tie in the FRP that bridges the crack and (ii) the additional friction that can be carried across the cracked masonry joint due to vertical confinement of the masonry by the FRP. Cracking of the masonry is accompanied by debonding of a band of FRP from the masonry, which propagates away from the diagonal crack so as to satisfy compatibility requirements as the crack opens (Fig 1a). The bond failure occurs within the weakest link of the adhesive joint, just below the surface of the masonry bricks (Fig. 1b).

The increase in strength due to bonded FRP can be useful, but it is also important to examine the ductility of the strengthened system, which has important implications for design. Perhaps the most obvious requirement for ductility is during an earthquake, when sustained energy dissipation is necessary under cyclic loading; however, ductility is also a fundamental requirement of structural design, as it underpins the lower-bound (or safe load) theory of plasticity, which allows design to proceed without understanding the exact equilibrium state provided stress redistribution can occur (Calladine, 1969). It is particularly important to recognize that both the FRP and the FRP-masonry bond failure are brittle and that the strengthened panel only displays ductility by virtue of frictional sliding between the two faces of the cracked masonry.

Furthermore, the brittle bond failure is sensitive to imperfections, which might be due to poor workmanship (such as poor surface preparation, inadequate wetting of the FRP or the FRP not being flat), or defects within the bricks. An additional consequence of the brittle bond failure is that the bond cannot dissipate energy once broken, which is of particular concern during multiple reverse loading cycles during

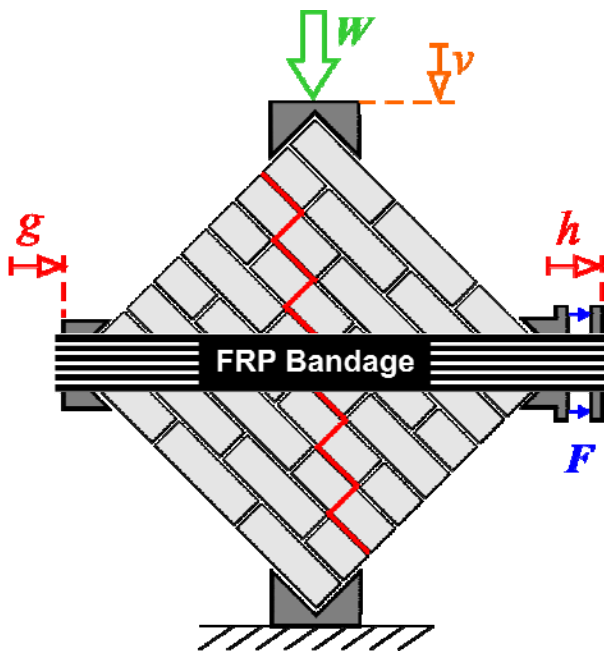
an earthquake. Whilst research (e.g.: Marshall *et al.* 1999) has demonstrated that bonded FRP strengthening can be used for laboratory applied cyclic loading, the stress state in a real structure during an earthquake could be very different. It is difficult to see how bonded FRP strengthening for real structures can be safely designed if it relies on brittle bond between the FRP and masonry.

The spread of the unbonded region of FRP strengthening can be halted, however, by introducing additional anchorage between the FRP and the masonry, for example by trapping sheet FRP beneath an FRP bar bonded into a horizontal joint (Khalifa *et al.*, 1999), or by splayed out bundles of fibres that are bonded into holes drilled in the masonry (Burr, 2004). The tests conducted by Stratford *et al.* (2004) similarly included anchorage along the top and bottom edges of the specimen that would not be present in a real structure. Hall *et al.* (2002) have demonstrated the use of a steel anchorage to trap the end of the FRP at the ground and to provide ductility to under-reinforced masonry buildings.

### STRENGTHENING MASONRY USING UNBONDED FRP ‘BANDAGES’

If the adhesive bond between the FRP and masonry needs to be supplemented with additional anchorages between the FRP and masonry, it is natural to question whether the FRP need be bonded to the masonry at all. Triantafillou and Fardis (1997) have proposed using unbonded FRP for whole-structure strengthening, and Lees *et al.* (2002) have demonstrated that unbonded prestressed FRP straps can be used to strengthen concrete beams in shear. The concept investigated in this paper is similar, using unbonded ‘bandages’ of FRP to increase the in-plane performance of a masonry panel.

Fig. 2 shows the specimen arrangement (the instrumentation will be described below). An FRP ‘bandage’ is wrapped around a masonry wallette specimen that carries in-plane shear-compression. The FRP acts as an elastic tie that carries tension and confines the cracked masonry. The bandage is unbonded, with a well-defined length between the anchorage points and is tensioned prior to testing.



(a) Schematic arrangement of the tests.



(b) Wallette specimen in the test machine, showing the FRP bandage and crack.

Fig. 2 FRP bandage strengthening applied to a masonry wallette.

## DESCRIPTION OF THE EXPERIMENTAL WORK

### Specimen fabrication

Seven wallettes were constructed from clay bricks ( $215 \times 100 \times 65\text{mm}$ , Young's modulus = 9GPa) and cement mortar. Each wallette was 3 bricks wide and 9 bricks deep, with 10mm mortar joints, giving a panel  $665 \times 665\text{mm}$ .

A series of 20 'triplet' specimens were also fabricated and tested to characterise the shear strength of the mortar joint (BS EN 1055-3, 2002). The triplet tests gave the following average peak shear strength ( $\tau_{peak}$ ) and post-peak residual shear strength ( $\tau_{residual}$ ) variation with confining stress ( $\sigma$ ):

$$\tau_{peak} = \tan 38^\circ \times \sigma + 1.90 \text{ N/mm}^2, \quad \tau_{residual} = \tan 30^\circ \times \sigma + 1.59 \text{ N/mm}^2 \quad (1)$$

The wallettes were strengthened using a high strength CFRP unidirectional tape fabric. The tape was saturated with an ambient-cure epoxy resin to allow load transfer between the fibres, and was 50mm wide, with a 0.2mm nominal thickness. The CFRP tape was tested in tension to determine its axial stiffness, giving an axial stiffness of 3.19kN/mm for a single layer of tape the same length as used on the wallettes.

The FRP bandage strengthening wrapped around the horizontal diagonal of the wallette. At the left side of the wall in Fig. 2a, the CFRP wrapped around a steel spreader, radiused to minimise stress concentrations in the CFRP. The CFRP bandage was closed by clamping and bonding to a steel plate at the right side of the wall. Four bolts allowed the steel plate to be pushed away from the wallette, applying tension to the CFRP. Strain gauges were bonded to the steel clamp arrangement to monitor the force in the bandage ( $F$  in Fig. 2a).

Table 1 lists the number of layers of CFRP bandage used for each specimen. It includes the initial bandage tension applied, as well as headline results that are described below. Specimen 1 was tested without CFRP; specimen 6 was unintentionally pre-cracked along the third mortar joint from the top during handling, but could nevertheless be tested.

Table 1 Details of the test specimens and headline results.

Test Number	Number of layers of CFRP in bandage	Initial Tension, $T$ (kN)	Load at first cracking (kN)	Peak Load (kN)	Displacement at failure (mm)
1	0	-	88		8
2	2	1.5	89	104	31
3	2	0.6	95	133	25
4	4	1.8	87	106	20
5	4	3.0	96	100	13
6	2	10	0 (pre-cracked)	103	12
7	4	7.4	101	122	15

### Test arrangement

The wallettes were loaded in compression ( $W$ ) across one of its diagonals using a 1000kN load-controlled universal test machine (Fig. 2). Steel spreader pieces were used to avoid crushing the corners of the masonry specimen. The applied load ( $W$ ), force in the bandage ( $F$ ), vertical displacement ( $v$ ), horizontal displacement at either end of the bandage ( $g, h$ ), were recorded during the test.

## EXPERIMENTAL RESULTS AND INTERPRETATION

The masonry wallettes all failed in broadly the same manner: a crack formed perpendicular to the tensile diagonal of the specimen (as in Fig. 2a) and the FRP bandage picked up load as the crack opened until the ultimate capacity of the FRP was reached. Failure of the FRP was at the clamped joint, due to the stress concentrations at that position. Table 1 gives further details of the load at which the first crack opening was observed, the peak recorded load, and the ultimate displacement for each test; Figs. 3 and 4 show the load-displacement results.

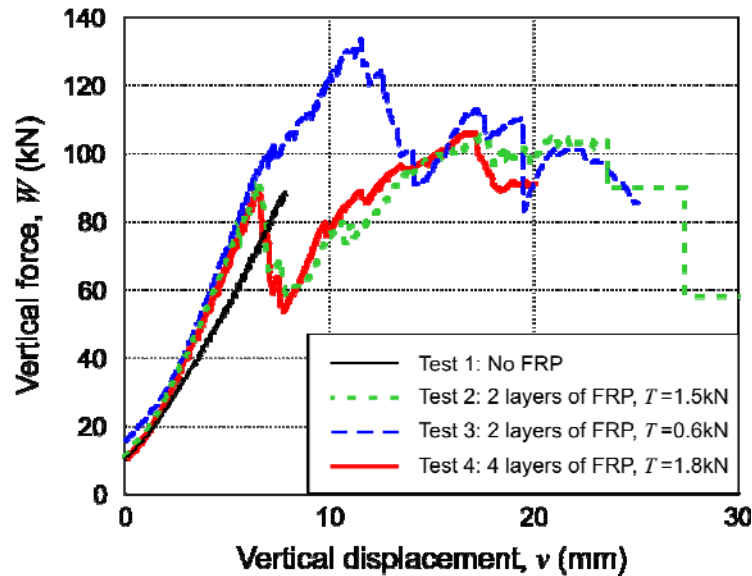


Fig. 3 Load - vertical deflection results for bandages with low initial tension.

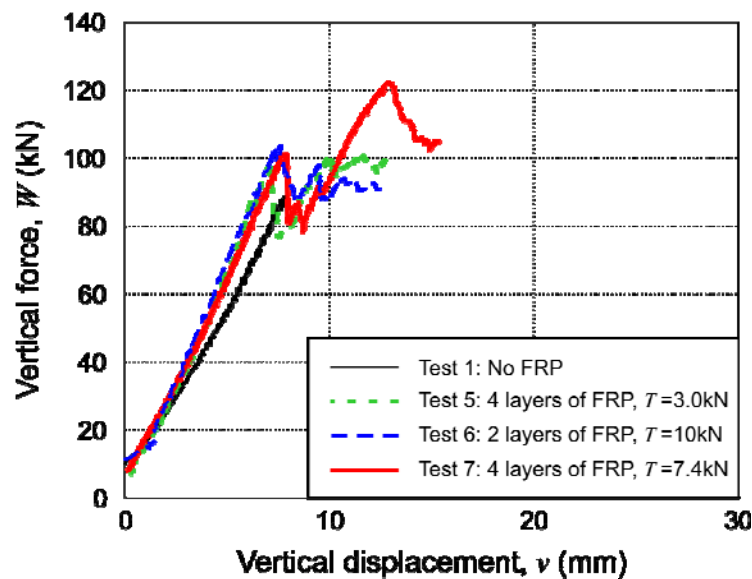


Fig. 4 Load - vertical deflection results for bandages with high initial tension.

The FRP had only a small effect on the load at which first cracking occurred compared to the plain masonry specimen (test 1), as is to be expected. After first cracking, there was a drop in the total load carried as the joint adhesion was broken and the masonry transferred to a frictional mode of stress transfer. As the vertical displacement and hence crack opening increased, the FRP stretched and picked up more load.

There was a modest increase in load capacity of the specimens, but more significant was the increase in deflection capacity due to the confinement provided by the FRP bandage. This was limited by the



deflection capacity of the FRP and consequently the specimens with low initial tension performed exhibited the greatest deflection capacity. It should be noted, however, that the FRP failed due to the stress concentration where the FRP was bonded and bolted between two steel plates, possibly resulting in variations between the tests.

Figs. 5, 6 and 7 focus upon the results from Test 3 (low initial tension, 2 layers of FRP), Test 4 (low initial tension, 4 layers of FRP) and Test 7 (high initial tension, 4 layers of FRP). Fig. 5 records the extension or stretch of the bandage, deduced from the difference in horizontal displacement between its two ends ( $h-g$ ). The figure confirms that the bandage makes little contribution prior to first cracking, with approximately linear stretching following cracking that indicates simple shearing along the cracked surface.

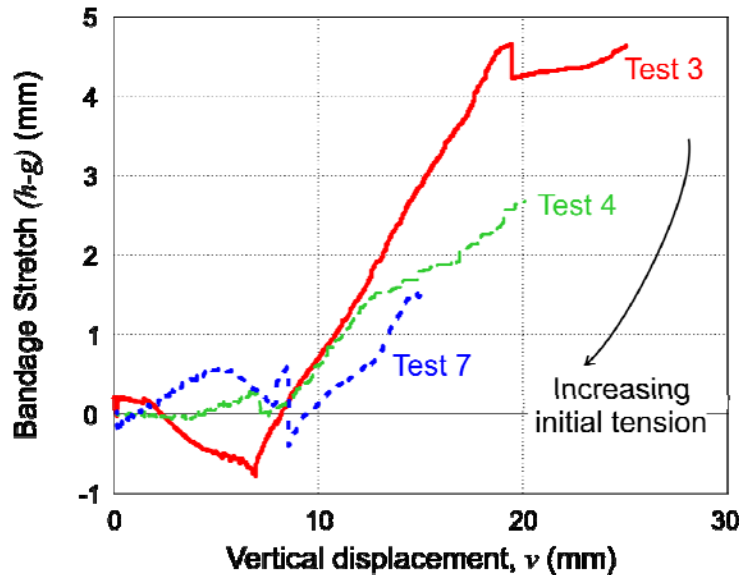


Fig. 5 Bandage extension.

Fig. 6 shows the force in the FRP bandage recorded using the strain gauges on the steel clamp, again showing that the bandage load remained at the initial tension until the crack formed. The plateauing of bandage force at high loads requires further investigation, but is believed to be due to a combination of slip in the FRP clamp, and progressive failure of the fibres in the FRP.

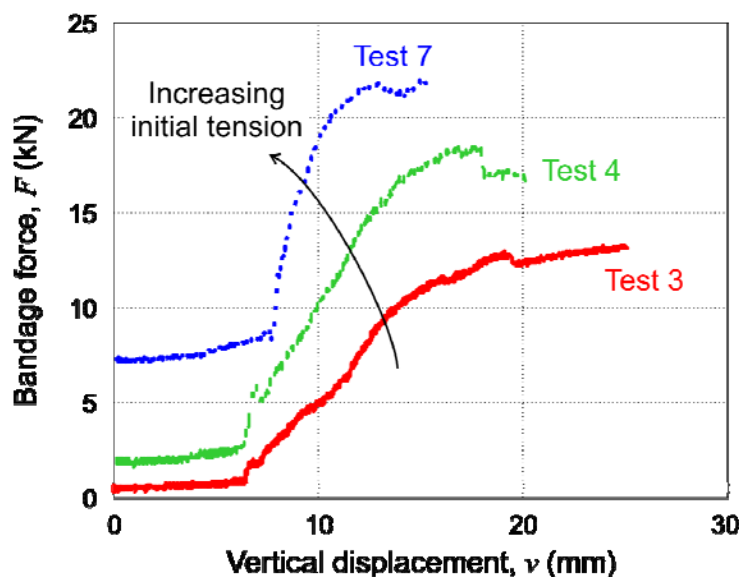


Fig. 6 The force in the bandage from strain gauge measurements.

Fig. 7 plots the ratio between the shear ( $S$ ) and normal ( $N$ ) forces acting across the diagonal cracked joint.  $S$  and  $N$  were derived by resolving the applied load ( $W$ ) and bandage force ( $F$ ) parallel and perpendicular to the masonry joint:

$$S = (W - F)/\sqrt{2}, \quad N = (W + F)/\sqrt{2} \quad (2)$$

The figure shows that once frictional sliding had developed across the crack, load was carried according to the angles of friction obtained from the triplet test results (Eqn. 1).

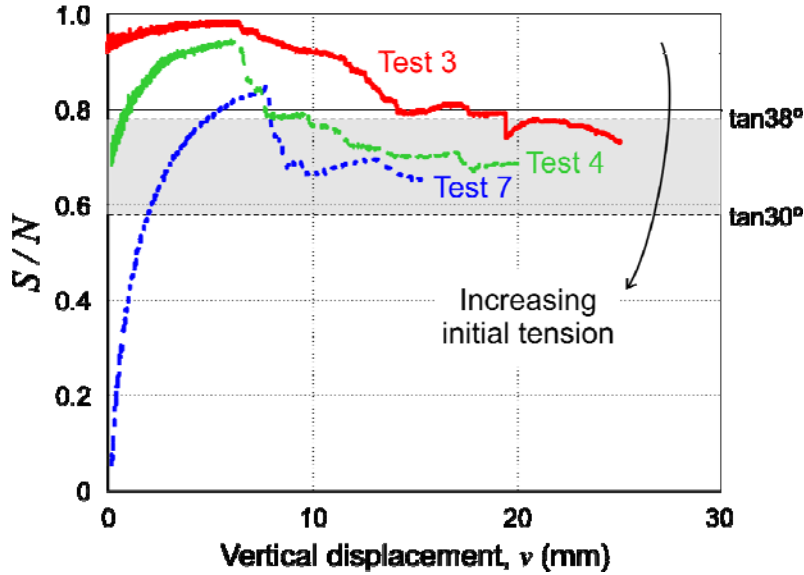


Fig. 7 The shear to normal force ratio across the cracked masonry. The grey band indicates the range of friction angle found from the triplet tests.

## DISCUSSION

The small series of tests presented here demonstrate the potential application of unbonded FRP to improve the in-plane performance of masonry panels. The method uses a low reinforcement ratio (0.03% for 2 layers of FRP), yet provides a significant increase in deformation capacity and a moderate increase in strength.

The experimental results demonstrate that design can be based upon the combination of two simple models:

- elastic stretching of the FRP bandage (limited by FRP rupture); and
- frictional sliding of the cracked masonry (based upon the residual friction).

Thus, the application of a FRP bandage scheme to a real structure will involve designing the unbonded length between anchorage points and the initial tension applied to the FRP, to ensure that the frictional ductility of the masonry is exploited prior to brittle failure of the bandage. It is envisaged that a number of masonry ‘bandages’ would be wrapped around a masonry panel, tailored to match the deformation capacity of the elastic FRP to the crack opening in the masonry. Bandages would be required along both diagonals to resist reversed loading. These might be hidden within the plaster applied to a typical structure.

The local details of the bandage will also require design. In the present tests the clamp arrangement used to close the bandage was crude and resulted in premature rupture of the bandager, but more refined mechanical fastenings that allow a greater proportion of the FRP rupture strain to be used are available. The bandage will either need to pass through holes made in the wall (involving far less irreversible damage than the surface preparation for bonded strengthening), or to be mechanical fastened to the surface of the masonry.



## CONCLUSIONS

The tests described in this paper demonstrate the use of unbonded FRP bandages as an alternative to bonded FRP for improving the in-plane shear performance masonry panels. Unbonded FRP retains many of the benefits of bonded FRP strengthening: the installation benefits of lightweight materials are retained, it is thin (and so can be hidden within finishing layers), and there are no corrosion concerns. It avoids using large quantities of adhesives and surface preparation.

## ACKNOWLEDGEMENTS

The experimental work was undertaken by Jonathan Conn, Jamie Scott, Gregor Sleight and James Wilkins as part of their MEng thesis projects, and the School of Engineering at the University of Edinburgh is thanked for its support of these projects. The Scottish Funding Council is acknowledged for its support of the Joint Research Institute, part of the Edinburgh Research Partnership in Engineering and Mathematics (ERPem).

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